An Experimental Investigation of Surface Pit Evolution During Cold-Rolling or Drawing of Stainless Steel Strip

R. Ahmed[1]

M. P. F. Sutcliffe

Cambridge University,
Department of Engineering,
Trumpington Street,
Cambridge, CB2 1PZ, U.K.

This paper presents an experimental investigation of the mechanisms of pit elimination in strip drawing and rolling of stainless steel strips. Strip drawing tests with artificial indents confirm the role of micro-plasto-hydrodynamic lubrication (MPHL) in allowing pits to be reduced in size and depth. The similarity of results for two oils, which differ in viscosity by a factor of 10, is attributed to the fact that oil is drawn out of the pits rather easily, so that the behavior tends to the unlubricated case. Similar behavior is observed for strip drawing of shot blast white hot band. For much smoother bright anneal strip, it is suggested that the presence of an oil film in the unpitted region prevents generation of pressure differences between the pits and the unpitted regions. A comparison of strip-drawn and cold-rolled stainless steel samples show that the change in pit area and R_q roughness varies with overall reduction in a remarkably similar way. The reason for such similar behavior is attributed to the absence of hydrodynamic action in preventing pit elimination, albeit for opposite reasons. The similar rate of pit evolution in both cases confirms the usefulness of the strip drawing rig as a tool to model the change of surface topography during rolling, as long as care is taken in matching the regimes of lubrication. [DOI: 10.1115/1.1327580]

Keywords: *Asperity, Metal Rolling, Strip Drawing, Friction, Lubrication, Surface Finish, Pit, Void, Stainless Steel*

1 Introduction

Control of surface finish is a primary concern in the manufacture of rolled stainless steel strip. Prior to cold rolling, the hot-rolled band is annealed, shot-blast and pickled, leaving a comparatively rough and broken surface. The bright finish or gloss required for many products is generated in subsequent passes as the smooth roll surface is imprinted on the strip surface. Figure 1, which is an optical micrograph of the surface of stainless steel strip, illustrates the large number of pits present after an intermediate pass. Further passes are needed to eliminate these pits, which significantly affect the visual appearance of the strip and may also play an important role in trapping lubricant during subsequent sheet forming operations. The evolution of these pits during a pass schedule has been studied experimentally by Fudanoki [1] and Ahmed and Sutcliffe [2]. The next section reviews details of the lubrication mechanisms controlling the change in roughness geometry. An additional factor which complicates the tribology in industrial rolling is the formation of a transfer layer on the surface of the roll [3]. For the purposes of investigating pit evolution, the effect of this layer can probably be ignored, although it will be important to ensure that an appropriate layer is formed in practice.

Lubrication Mechanisms in Rolling. Lubricant is applied during rolling to reduce friction and wear of the rolls and to prevent galling of the strip surfaces. In order to achieve the high gloss required, it is essential there is only a very thin film of oil separating the rolls and strip in the bite, so that there is significant asperity contact between rolls and strip. The rate at which pits are eliminated during rolling depends on both the mechanics of asperity crushing and on the role of lubricant. In the absence of bulk deformation, crushing of asperities is rather difficult. With even a modest bulk strain, however, the asperities can be rapidly eliminated [4,5]. Both theory and experiments show that the long wavelengths of roughness are more easily crushed, while the small scale features, for example pits on the surface, will be more difficult to eliminate [6]. There are at least three mechanisms in rolling which determine the lubricant pressure in the pits and their potential elimination: (i) hydrodynamic entrainment of oil in the inlet, (ii) hydrodynamic action inside the pits due to relative sliding in the bite, and (iii) hydrostatic action in isolated pits.

Figure 2 shows a schematic of the roll bite. At higher speeds, hydrodynamic entrainment in the inlet tends to keep the surfaces separated and prevents effective flattening of the asperities on the strip. The amount of oil drawn in by entraining action at the inlet to the bite can be estimated by the ''smooth film thickness'' estimate h_s of Wilson and Walowit [7]

$$h_s = \frac{6\,\eta_0 \alpha \overline{u}}{\phi(1-\exp(-\alpha Y))}, \tag{1}$$

where $\overline{u}=(u_r+u_s)/2$ is the average entraining velocity, ϕ is the inlet angle between the strip and tool (it is assumed that $\tan\phi \approx \phi$), Y is the plane strain yield stress of the strip and η_0 is the viscosity of the lubricant at ambient pressure. α is the pressure viscosity coefficient in the Barus equation $\eta=\eta_0\exp(\alpha p)$ used to describe the variation of viscosity with pressure p. The ratio $\Lambda_i = h_s/\sigma_0$ of the smooth film thickness h_s to the combined tool and initial strip roughness σ_0 can be used to characterize the lubrication regime associated with oil entrainment in the inlet. To achieve the very smooth surfaces required, rolling typically operates with very thin oil films, with $\Lambda_i \ll 1$. Refinements to this model allow for the effect of roughness in the contact [8,9]. These

[1] Current address: Department of Mechanical and Chemical Engineering, Heriot-Watt University, Riccarton, Edinburgh, EH14 4AS.

Contributed by the Tribology Division for publication in the ASME JOURNAL OF TRIBOLOGY. Manuscript received by the Tribology Division February 15, 2000; revised manuscript received June 29, 2000. Associate Editor: R. C. Ovaert.

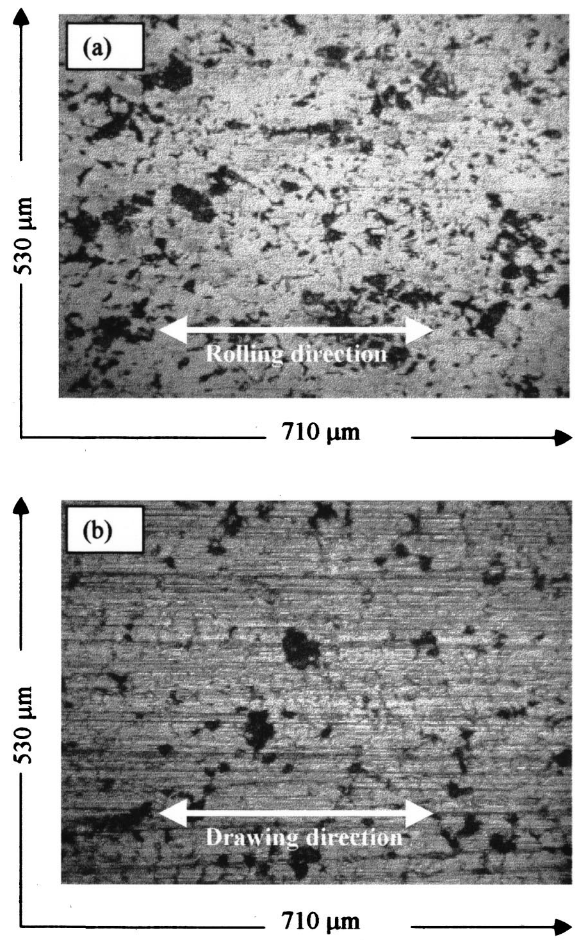

Fig. 1 Optical micrographs of white hot band after an overall reduction of approximately 30 percent: (*a*) cold rolled; (*b*) Strip drawn using Vitrea 68 oil in a three-pass schedule.

analyses show that Eq. (1) gives a reasonable estimate of the film thickness even in the practical situation with the roughness much larger than the film thickness.

At lower speeds, there is considerable contact between the surfaces and isolated pits develop on the strip surface. Lo [10] identifies a ''percolation threshold,'' below which isolated pits will form. This mechanism is particularly relevant to rolling of stainless steel, where the surface generated after shot-blasting and pickling encourages pit formation. Build-up of hydrostatic pressure in the pits as they are reduced in volume tends to prevent the pits being eliminated [11]. However, in the presence of sliding between the tool and strip, this oil can be drawn out of the pits due to hydrodynamic action, as illustrated schematically in Fig. 2. This mechanism has been described as micro-plasto-hydrodynamic lubrication (MPHL). Various experimental [1,12–15]

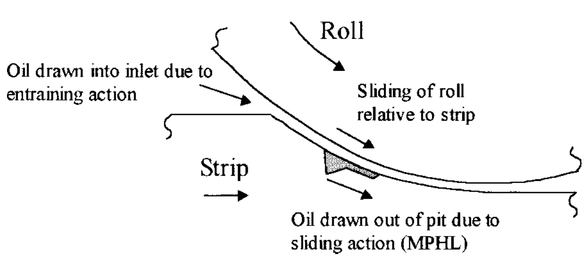

Fig. 2 Schematic of inlet and MPHL lubrication mechanisms

studies have considered MPHL, frequently using artificial indents to help observe the phenomenon. Lo and Wilson [16] derive a theoretical model using hydrodynamic theory, showing how pit crushing depends on pit geometry and hydrodynamic conditions. Pits are progressively eliminated as sliding proceeds, with the rate at which the oil is drawn out of the pit, and hence the rate of asperity crushing, increasing with increasing sliding speed and oil viscosity. This contrasts with the effect of hydrodynamic entrainment in the inlet, where increasing speed results in less crushing. By analogy with the hydrodynamic theory used to derive Eq. 1, we can write down an order-of-magnitude estimate of the film thickness h_1 at the trailing edge of the pit as

$$h_1=\frac{6\,\eta_0\alpha\Delta u}{\phi_p(\exp(-\alpha Y/2)-\exp(-3\alpha Y/2))}, \tag{2}$$

where it is assumed that the lubricant pressures in the pits and on the asperity tops are given, for this order of magnitude estimate of film thickness, by $Y/2$ and $3Y/2$, respectively. In practice these pressures will depend in a complicated way on the asperity crushing and lubrication details. Furthermore, the estimate is very sensitive to this assumption due to the exponential terms, so that the estimate of the film thickness should be treated as very approximate. The relevant entraining angle ϕ_p is that at the edge of the pit (it is assumed that tan $\phi_p\approx\phi_p$) and the appropriate entraining velocity is equal to the sliding speed between tool and workpiece Δu. Assuming that pits are valleys running transversely to the rolling direction, the volume of oil drawn out from the pit, per unit width of strip, as it travels through the bite can be approximated by $\Delta\ell h_1/2$, where $\Delta\ell$ is the sliding distance and the factor of two arises because the mean speed of the film is half the sliding speed. The initial pit volume, per unit width of strip, is approximately equal to $\delta^2/2\phi_p$, where δ is the pit depth. To characterize lubrication in the MPHL regime, we define a lubrication parameter Λ_m, akin to Λ_i for the inlet analysis, as the ratio of the oil drawn out of the pit to the initial pit volume:

$$\Lambda_m=\frac{6\,\eta_0\alpha\Delta u\Delta\ell}{\delta^2(\exp(-\alpha Y/2)-\exp(-3\alpha Y/2))}. \tag{3}$$

We expect MPHL effects to be insignificant when Λ_m is small.

Sheu et al. [17] examine the details of pit elimination both theoretically and experimentally for larger cavities superimposed on a smaller scale of roughness. In their model, oil can be trapped in the larger pits and then drawn out along a network of channels on the surface, leading to significant interaction between two scales of roughness. Hence this model combines the MPHL modeling approach with the ideas used to estimate the effect of roughness on the film generated in the inlet to the bite.

Strip Drawing. Lancaster and Rowe [18] present an experimental study of strip drawing using lubricants containing soaps and fatty acids. They observe MPHL from a spherical indentation on the surface, showing how soap trapped in the pocket is drawn out from the trailing edge during drawing. A similar effect is seen for grit-blasted surfaces. Thomson et al. [19] compare the strip drawing and cold rolling processes. They suggest that the main source of poor surface finish in drawn wire is longitudinal scratches caused by the die. The similarity of the strip-drawing and rolling processes suggests that strip drawing might be a useful tool to simulate the change in pit geometry during rolling. As this process is easier to control under laboratory conditions than rolling, it is an attractive way to understand the tribology of rolling. However it is worth noting that there are significant differences in the sliding speed and relative sliding motion between the two cases, with the reversal of sliding direction common in rolling not encountered in drawing. Moreover, the ploughing behavior indicated by the longitudinal scratches frequently observed in drawing may not be typical of rolling, where there is a much smaller sliding distance between roll and strip. By maintaining a very good surface finish on the dies, this behavior is largely overcome in these experiments. However this difference between rolling and drawing could be critical where the surface of the contact areas is considered.

This paper presents an experimental investigation of pitting in both rolling and strip drawing. The aims of the work are twofold; firstly, to compare pit evolution in the two processes and so establish the usefulness of strip drawing as a tool to look at cold rolling. Secondly, the paper investigates the mechanisms controlling the evolution of the pits.

2 Experimental Details

2.1 Strip Drawing and Plane Strain Compression. The strip drawing rig described in [18] is used to perform both strip drawing and plane strain compression tests. Details of the rig and the experimental methods used are described in the following sections.

Strip Drawing Rig. Figure 3 shows a schematic plan view of the strip drawing rig. The drawing dies are held in rigid die holders, one fixed to a stationary housing and the other attached to an indentation ram. The specimen is held between these dies via a wedge grip arrangement to a shackle attached to the rigid drawing frame. The drawing frame is pushed in the horizontal direction by hydraulic drawing rams at either end, which are in turn attached to the housing. The drawing and indentation rams are separately driven hydraulic cylinders, each with a maximum capacity of 100 kN. The drawing and indentation forces are measured using strain gauge bridges on the shackle and fixed die holder.

Strip Drawing Dies. Three sets of En 31 steel dies were used during this investigation, with wedge semi-angles ϕ of 4 deg, 6 deg, and 10 deg. This variation in wedge angle was used to vary the lubricant film thickness, via Eq. (1). The strip drawing rig was also used for plane strain compression tests by indenting the specimen with a pair of flat-faced dies, which had a face length of 5 mm and spanned the width of the specimen. The dies were carefully polished before testing, with a typical R_q roughness value of 0.08 μm.

Strip Material. Stainless steel (316 grade) strips of length 250 mm, width 20 mm, and thickness either 3 or 4.1 mm were used as test specimens. The 3 mm thick specimens were of bright-annealed cold rolled sheet, with an R_q roughness of 0.2 μm. The 4.1 mm thick specimens strips were annealed and shot blasted ''white-hot band,'' with an initial R_q roughness of approximately 7.5 μm. In both cases the strips were cut so that the original rolling direction ran along the length of the specimens. The plane strain yield stress for this grade of steel is around 950 MPa after a bulk strain of 30 percent. In some of the tests artificial features were produced on the strip surface using Vickers and Brinell indentations at a load of 20 and 15 kg, respectively.

Lubricants. Three different mineral oil lubricants were used, namely a gear oil HVI 650, a thinner general-purpose oil Vitrea 68, and a rolling oil Genrex H12. The HVI 650 and Vitrea 68 were base oils, while the Genrex contained a typical additive package. The viscosity and pressure viscosity coefficients for these lubricants are summarized in Table 1. The viscosities of the oils are taken from manufacturers' data sheets, extrapolated to lower temperatures where necessary. The pressure viscosity coefficient of HVI 650 is taken from [20], while the values for the Vitrea 68 and Genrex have been estimated by comparison with similar oils [20,21].

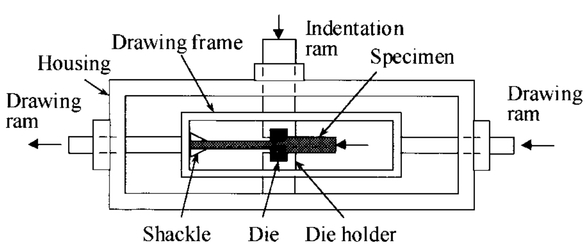

Fig. 3 Schematic of the strip drawing rig

Table 1 Lubricant properties

	HVI 650	Vitrea 68	Genrex H12
η_o at 25 °C (Ns/m^2)	1.3	0.135	0.01
α (m^2/N)	3.29×10^{-8}	(2.2×10^{-8})	(1.5×10^{-8})

Test Procedure. Prior to drawing, the die and strip surfaces were cleaned with acetone and then painted generously with lubricant. The specimen was first loaded up using the indentation ram and then drawn through the dies at a steady speed of 17 mm/s. Where several passes were applied to the specimen, it was relubricated between passes. The dies were re-polished after a few draws to prevent a build-up of transfer films. This procedure was adopted to simulate the industrial situation where, although stable transfer films generally develop on the rolls, they are rather thin and do not significantly affect the roughness of the roll surface. During multi-pass drawing, samples were drawn in the same direction, as for tandem mill operations, in contrast to the change in sliding direction from pass to pass found on reversing mills.

2.2 Rolling. Ahmed and Sutcliffe [2] have described the details of the samples obtained from an industrial rolling mill. Samples of austenitic stainless steel sheet (material 18/8, 302), of width 1.3 m and initial thickness 4.0 mm, were collected at various intermediate stages of the manufacturing operation. The hot band was annealed, shot-blasted and pickled prior to being cold rolled in a 20-high Sendzimir mill to a final thickness of 1.5 mm. The work rolls used for the passes presented here were approximately 50 mm in diameter and were ground after the first pass to an R_q roughness of about 0.15 μm. The samples were collected at the very end of the coil where the rolling speed is very low, so that lubrication conditions are not typical of the bulk of the coil.

2.3 Surface Roughness Measurements. Surface roughness was measured in a Zygo non-contacting three-dimensional interferometric profilometer. The R_q roughness is estimated from the sample area of 0.26×0.34 mm, after subtracting the mean plane. The change in geometry of Vickers or Brinell indents was also measured using the three-dimensional profilometer. We use here the method described by Ahmed and Sutcliffe [2] for identifying surface features on stainless steel strip. By adopting an automatic algorithm, the analysis is quicker, more objective and more accurate than alternative visual methods. In brief, a matrix containing surface height data is obtained by three-dimensional profilometry and then exported to a software package to calculate a matrix of pit depths d, relative to the surrounding area. A given data point is identified as being in a pit when the depth of the pit is greater than a critical value, here taken as 0.5 μm. The pit area is then expressed as a proportion of the total area of the sample.[1] Results for typical cold-rolled stainless steel sheet [2] showed that the method effectively identified those pits which could be clearly observed on scanning electron micrographs of the strip surface. The pit area was estimated using an average of three measurements, each over an area of 0.34×0.26 mm. The three were typically within 10 percent of each other.

3 Results

The aim of the work is both to validate strip drawing as a tool to investigate pit evolution in rolling and to examine some of the

[1]The pit area presented here corresponds to what is described as the ''deep pit'' area by Ahmed and Sutcliffe [2].

key variables influencing the change in pit geometry. Before making a comparison between the two processes, it is first necessary to establish the relevant lubrication mechanisms for the two sets of experiments. Results are first presented for artificial indents, to establish the details of hydrostatic lubrication and MPHL. These are followed by measurements on the white-hot band, which has a shot blast surface finish, and on the much smoother bright annealed strip, to identify the lubrication mechanisms observed here. Finally, a comparison is made between rolling and strip drawing results.

3.1 Hydrostatic Oil Pressure. Plane strain compression was used to confirm the effect of lubricant entrapment on pit crushing, without the additional complication of sliding in the bite giving rise to MPHL. Tests were carried out both on bright-annealed strip containing artificial indents and on shot-blast white-hot band. Table 2 shows the effect of lubrication on the reduction in the volume of Vickers indents on bright annealed strip due to a reduction in strip thickness of 30 percent. The presence of lubricant considerably reduces the ease with which these artificial indents can be crushed. Figure 4 shows the effect of lubrication on the evolution of pit area and R_q roughness with overall reduction (i.e., (initial-current)/initial strip thickness) for the shot-blast finish of the white-hot band. The proportion of pits steadily falls as they are crushed or ''converted'' into shallow pits less than 0.5 μm in depth. The fall in R_q roughness reflects the reduction in pit depth and area. The lubricant reduces the rate of pit crushing for these stochastic surfaces in a similar, although less dramatic way to that observed for the artificial indents.

The effect of lubricant in reducing the rate at which pits are eliminated on both bright anneal strip with artificial indents and shot-blast white hot band confirms that oil can be trapped hydrostatically, as suggested by Kudo [11]. The greater reduction in indent volume for the thinner Genrex oil may be due to enhanced leakage of oil from under the indents, in the manner proposed by Sheu et al. [17].

3.2 Micro-Plasto-Hydrodynamic Lubrication (MPHL) With Artificial Indents. This section describes observations of MPHL during strip drawing of bright anneal strip containing Vickers or Brinell indentations. Table 3 shows the change in volume of the indents after a single-pass reduction of 30 percent, using a variety of lubricants. The values of the MPHL lubrication parameter Λ_m are included in Table 3, using the indent geometry to estimate an appropriate pit depth and angle. The inlet parameter Λ_i, based on the roughness of the indents, is very small for these conditions. Figure 5 illustrates typical indents after drawing. The dark ''comet tails'' at the trailing edge of the indents are areas of greater roughness, caused by the oil drawn out of the indents during sliding. Table 3 includes the area of these MPHL regions and the roughness both inside and outside these regions. The increased roughness in the MPHL area gives an indication of the thickness of the oil film drawn out of the pits. Table 3 shows that, for these conditions: (i) the pit is considerably reduced in volume during drawing, (ii) the amount of oil drawn out of the contact and the roughness of the MPHL region is significantly less for the thinnest Genrex oil, but similar for the thicker HVI 650 and Vitrea 68 oils, (iii) the effectiveness of MPHL varies significantly with pit geometry (e.g., comparing results for Brinell or Vickers indentors, or for the two orientations of the Vickers indentor), and (iv) the change in pit volume is much less sensitive to lubrication conditions than is the R_q roughness and area of the MPHL region, so that more reliable inferences can be made from the later observations.

Table 2 Reduction in volume of Vickers indents on bright-annealed strip after a reduction in thickness of 30 percent in a plane strain compression test

Dry	HVI 650	Vitrea 68	Genrex
94%	49%	50%	56%

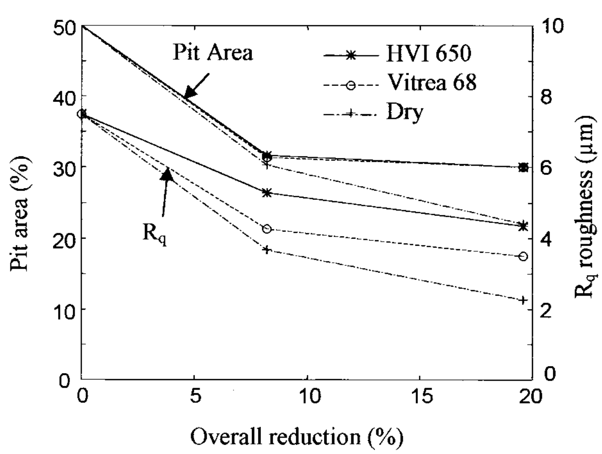

Fig. 4 Effect of lubricant on the evolution of pit area and R_q roughness with overall reduction for plane strain compression of white hot band

Table 3 Strip drawing results for artificial indentations on bright-annealed strip with a single-pass reduction of 30 percent and a die angle of 6 deg. The MPHL regions correspond to areas where oil is drawn out of the indents.

Lubricant	Λ_m	Reduction in volume of indent (%)	Area of MPHL region ($10^6 \mu m^2$)	R_q inside MPHL region (μm)	R_q outside MPHL region (μm)
Vickers - Drawing direction parallel to edge					
HVI 650	$> 10^3$	76	1.9	0.53	0.26
Vitrea 68	3	78	2.1	0.55	0.27
Genrex	0.01	76	0.62	0.32	0.14
Vickers - Drawing direction parallel to diagonal					
HVI 650	$> 10^3$	77	1.6	0.38	0.26
Vitrea 68	4	82	1.5	0.45	0.27
Genrex	0.01	82	0.62	0.31	0.14
Brinell					
HVI 650	$> 10^3$	97	1.4	0.54	0.26
Genrex	0.04	92	0.6	0.24	0.14

These observations of MPHL using artificial indents confirm previous experimental work [e.g. 4, 15, and 18], showing how MPHL drags oil out of the pits during drawing. The reduction in MPHL area and roughness for the Genrex lubricant, as compared with the two thicker oils, reflects the change in the value of the MPHL parameter Λ_m from a very small value for Genrex to values of around 3 for Vitrea 68 and greater than 10^3 for HVI 650 oils. The similarity of results for the two thicker oils, despite the fact that their viscosities differ by a factor of more than 10, can be understood with reference to their relatively large values of Λ_m. In these circumstances, it is easy to draw oil out of the pits, so that there is no chance for oil pressure to build up in the pits. Instead the rate at which the asperities can be crushed approaches the limit for unlubricated conditions.

3.3 Strip Drawing of White-Hot Band and Bright Annealed Strip. In this section we investigate the change in surface finish during drawing of steel strip with roughness typical of industry. Tables 4 and 5 detail the pass schedule for white-hot band drawn using either HVI 650 or Vitrea 68 oil. It proved impossible to draw these as-received strips with Genrex lubricant, as the higher friction between die and strip tended to cause the strips to break during the draw. The effect of lubricant on the change in pit area and R_q roughness with overall reduction is

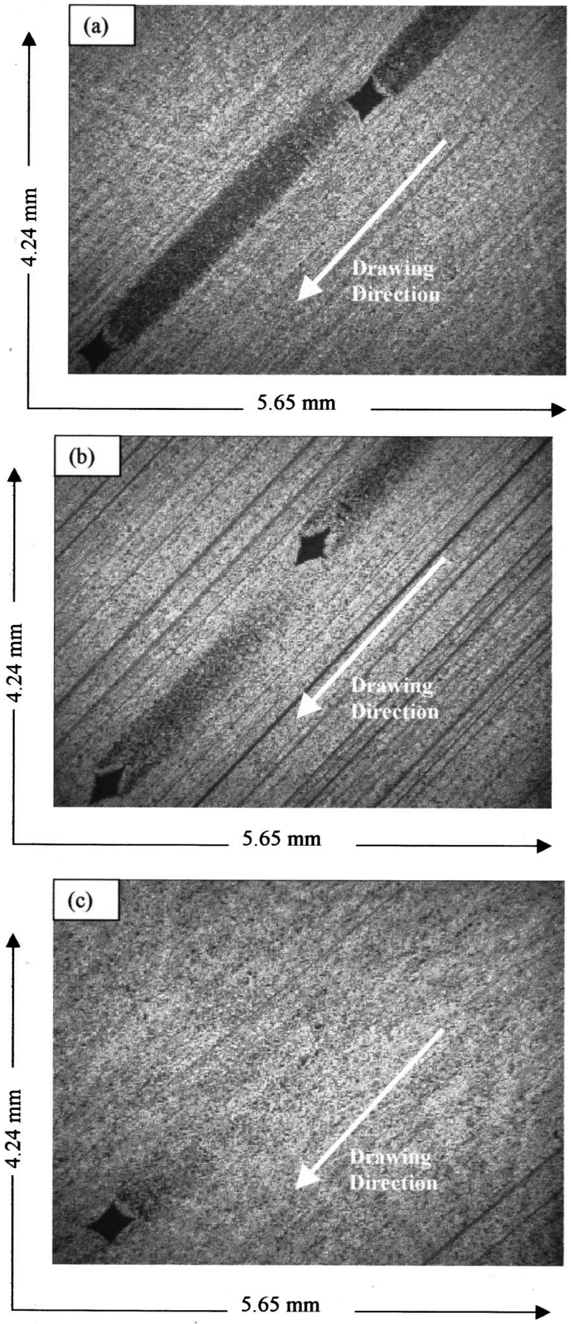

Fig. 5 MPHL lubrication of Vickers indents on bright annealed strip after strip drawing with a 30 percent single-pass reduction: (*a*) Vitrea 68, indent side parallel to sliding direction; (*b*) Vitrea 68, indent diagonal parallel to sliding direction; (*c*) Genrex.

shown in Fig. 6. The bulk strain during drawing allows the pits to be rapidly eliminated, with a corresponding reduction in R_q roughness. Although there is a factor of more than 10 in viscosity between the two lubricants, the rate of pit crushing is similar for the two oils. Values of the MPHL and inlet lubrication parameters Λ_m and Λ_i are included in Tables 4 and 5. In estimating Λ_m, the pit depth δ has been taken equal to the strip R_q roughness and the pit angle ϕ_p equal to a typical value of 15 deg. For these conditions the inlet parameter Λ_i is of the order 0.001 for the Vitrea 68 and 0.01 for the HVI 650 oil. The pit MPHL parameter Λ_m is 80 for the first pass using Vitrea 68 and much greater than this in all other cases.

Table 4 Strip drawing results for white-hot band with HVI 650 lubricant. The die angle is 4 deg for passes 1 to 3 and 10 deg for the final pass

Draw no.	Inlet thickness (mm)	Reduction (%)	Λ_i	Λ_m
1	4.1	15.3	0.004	$> 10^3$
2	3.47	10.9	0.012	$> 10^3$
3	3.09	10	0.024	$> 10^3$
4	2.78	14	0.018	$> 10^3$

Table 5 Strip drawing results for white-hot band with Vitrea 68 lubricant and a die angle of 4 deg

Draw no.	Inlet thickness (mm)	Reduction (%)	Λ_i	Λ_m
1	4.1	15.1	0.0003	80
2	3.48	9.7	0.0007	1×10^3
3	3.14	9.5	0.002	$> 10^3$

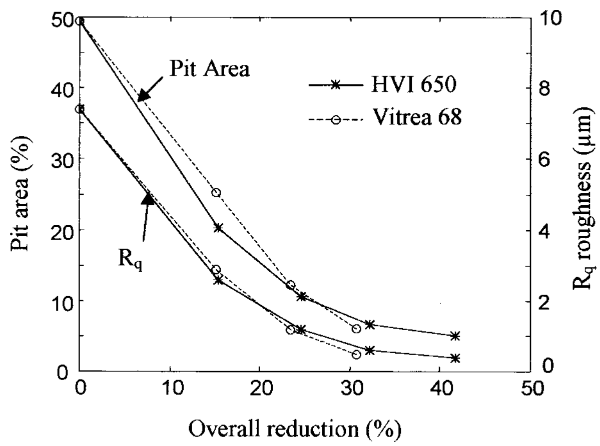

Fig. 6 Effect of lubricant on the evolution of pit area and R_q roughness with overall reduction for strip drawing of white hot band

Table 6 gives similar results for bright-annealed strip, showing the change in roughness amplitude and pit area after drawing with a single-pass reduction of 30 percent.[2] Table 6 shows that the area of pits is not reduced significantly with either the HVI 650 and Vitrea 68 oils, indeed it appears to increase slightly. However, the pit area is significantly reduced with the least viscous Genrex oil. Similarly the roughness is only reduced significantly for the Genrex oil and rises slightly for the two thicker oils. The inlet parameter Λ_i changes from 0.0004 for the Genrex to 0.1 for the HVI 650 lubricant. The pit lubricant parameter Λ_m is large in all cases.

To understand the contrasting behavior of these two rough surfaces we need to consider in more detail the lubrication mechanisms of oil film generation in the inlet and at the edge of the pits in the bite. For the tests on white hot band, Tables 4 and 5 and Fig. 6, in all cases the MPHL parameter Λ_m is large and the inlet lubrication parameter Λ_i is small, so that we should expect the lubrication mechanisms in both cases to be similar, with the pits behaving in an isolated manner. As with the artificial indents, Table 3, the slight differences between the two oils, despite the big difference in their viscosities, reflects the way in which the crushing behavior is limited by dry contact conditions. The large

[2]In practice, the specimens containing the artificial indents of Section 3.2 were used for this set of results, taking measurements well away from any indents.

Table 6 Strip drawing results for bright-annealed strip with a single-pass reduction of 30 percent and a die angle of 6 deg. The strip initially had an R_q roughness of 0.2 μm and pit area of 3.5 percent.

Lubricant	Λ_i	Λ_m	R_q after draw (μm)	Pit area (%)
HVI 650	0.1	$> 10^3$	0.26	4
Vitrea 68	0.007	$> 10^3$	0.27	5
Genrex	0.0004	1×10^3	0.14	1

values of Λ_m imply that oil can be drawn out of the pits rather easily, so that little oil pressure is generated there.

Turning to the tests with the two thicker lubricants on the bright annealed strip, Table 6 shows that the pits are not eliminated during drawing. The higher values of lubrication inlet parameter Λ_i suggest that the film generated at the inlet to the bite between the contact areas may be too great for the pits to behave in an isolated manner, so that the MPHL mechanism does not apply directly. Probably the roughening of the surfaces is associated with the relatively thick oil films generated either from these inlet conditions or at the trailing edge of the pits (c.f. the high roughness found in the MPHL region of the artificial indents, Table 3). To model this behavior, both the inlet entraining action and the interaction between the MPHL mechanism and the flow of oil along channels in the contact areas should be considered, following the analysis of Sheu et al. [17]. For the corresponding tests with the much thinner Genrex oil, however, there is no significant oil film generated at the inlet and the pits are isolated in the bite. With the high value of MPHL lubricant parameter Λ_m, further crushing ensues as oil is drawn out of them in the bite. Clearly further work is needed to confirm these suggestions.

3.4 Comparison of Cold Rolling and Strip Drawing. Having investigated the mechanisms of pit elimination, we are now in a position to compare results for strip drawing and rolling. The aim of this comparison is to establish strip drawing as a useful simulation tool for rolling. Figure 7 compares the evolution of pit area and R_q roughness with overall reduction for strip-drawn and cold-rolled strip, in both cases starting from shot-blast white hot band (albeit with slightly different grades of stainless steel). The strip drawing results are for HVI 650 lubricant. Figure 1 shows optical micrographs of the drawn and rolled surfaces after similar overall reductions of approximately 30 percent. Both the change in pit area and the appearance of the pits is remarkably similar in the two cases. The good correlation between the two sets of data can be understood with reference to the lubrication mechanisms, where in both cases we expect the behavior to be rather similar to dry rolling. For the rolled samples, this arises because samples were taken from the end of the coil where the rolling speed is small. For the strip-drawn samples, it is suggested in Section 3.3 that, for these conditions, oil is drawn out of the pits too quickly for pressure to build up there. The similarity in the way that pits are crushed with the two processes gives a good deal of confidence in using the strip drawing rig as a simulation tool for rolling. However the discussion above highlights the need for a careful understanding of the appropriate lubrication mechanisms in making such comparisons.

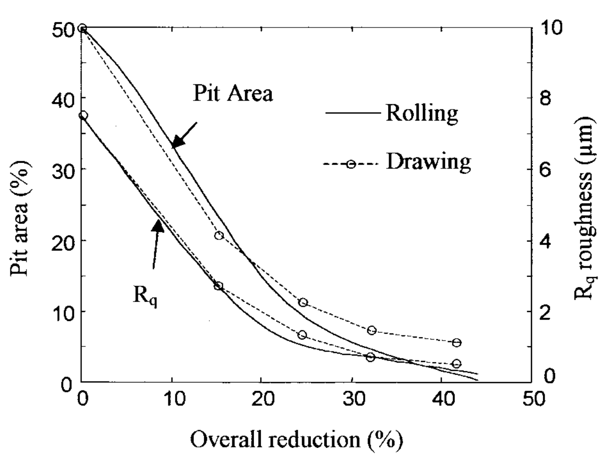

Fig. 7 Comparison of the evolution of pit area and R_q roughness with overall reduction for rolling or strip drawing of white hot band. Strip drawn results are for HVI 650 lubricant.

4 Conclusions

This paper presents an experimental investigation of the mechanisms of lubrication in strip drawing and rolling of stainless steel and their influence on the rate at which pits on the surface are eliminated. Lubricant was seen to reduce the rate of crushing of both artificial indents on a smooth surface and the rough shot-blast surface during plane strain compression tests, confirming the role of hydrostatic pressure in preventing pit elimination.

Strip drawing tests with artificial indents confirmed the presence of micro-plasto-hydrodynamic lubrication (MPHL). The sliding action in the bite was seen to draw oil out of the pits, forming a rougher patch at the trailing edge of the bite and allowing the pit to crush more rapidly. Results are interpreted in terms of an inlet lubrication parameter Λ_i, expressing the ratio of inlet film thickness to combined tool and strip roughness and an MPHL parameter Λ_m, expressing the ratio of the initial pit volume to the pit volume drawn out in the bite due to sliding. The similarity of results for the two thicker oils, despite a factor of 10 difference in viscosity, is attributed to the fact that Λ_m is relatively large in these cases. Oil is drawn out of the pits rather easily and little pressure is generated in the bottom of the pits, so that the behavior tends to the limiting case of dry conditions. Similar behavior is observed for strip drawing of shot blast white hot band. For much smoother bright anneal strip, however, it is seen that pits are not significantly eliminated when drawing using the thicker oils, while drawing with a thin oil does allow further elimination of pits. In these tests it is suggested that the presence of an oil film in the unpitted region, as indicated by the relatively large value of inlet parameter Λ_i, prevents the pits behaving in an isolated manner. The contrast between the strip drawing results and the plane strain compression tests confirm the importance of relative sliding in eliminating the pits.

The variation of pit area and R_q roughness with overall reduction is very similar for strip-drawn and cold-rolled stainless steel samples. Moreover there is a strong resemblance in the micrographs of the two strip surfaces. This similarity is attributed to the absence of hydrodynamic action in preventing pit elimination, albeit for opposite reasons. In the rolling tests, samples were taken at very slow speed so that hydrodynamic effects would be insignificant, while for the strip drawing tests the large values of MPHL parameter Λ_m indicate that the oil was easily drawn out, with behavior approaching dry conditions. Results confirm the usefulness of the strip drawing rig as a tool to model the change of surface topography during rolling, as long as this is combined with a clear understanding of the relevant regimes of lubrication. It is essential that more complete theoretical models of the lubrication process are developed to understand the influence of the pit geometry on asperity crushing and to model interaction between the inlet and MPHL effects.

Acknowledgments

The authors are most grateful for the help of Dr. Derek Smith, Dr. John Williams, Dr. Huirong Le and Mr. Fotios Georgiades and for the input from Dr. Didier Farrugia, Mr. Ken King and others at the collaborating companies (Corus plc, Swinden Technical Center and Avesta Sheffield). The financial support of the collaborating companies, the Engineering and Physical Sciences Research Council and the Isaac Newton Trust is gratefully acknowledged.

Nomenclature

d = matrix of pit depths
h_s = film thickness generated in inlet
h_1 = film thickness generated at trailing edge of pit
R_q = r.m.s. amplitude of surface roughness
$\bar{u}$ = mean entraining velocity at inlet to bite
Δu = sliding velocity between tool and strip in bite
$\Delta \ell$ = sliding distance in bite
Y = plane strain yield stress of strip
α = lubricant pressure-viscosity coefficient or index
ϕ = angle between tool and strip at the inlet to the bite
ϕ_p = pit slope
$\eta(\eta_0)$ = viscosity of lubricant (at ambient pressure)
Λ_i = inlet lubrication parameter: ratio of inlet film thickness to combined tool and strip roughness
Λ_m = MPHL lubrication parameter: ratio of an estimate of the volume of oil drawn out of the pit due to micro-plasto-hydrodynamic lubrication to the initial pit volume
σ_0 = initial combined R_q roughness of tool and strip

References

[1] Fudanoki, F., 1997, ''Development and Evaluation of Model for Mechanism of Formation of Surface Properties of Cold-Rolled Stainless Steel,'' *First International Conference on Tribology in Manufacturing Processes*, Gifu, Japan, pp. 378–383.
[2] Ahmed, R., and Sutcliffe, M. P. F., 2000, ''Identification of Surface Features on Cold Rolled Stainless Steel Strip,'' Wear, **244**, pp. 60–70.
[3] Rizoulières, B., and Montmitonnet, P., 1999, ''Couches de transfer et frottement en laminage à froid des aciers inoxydables,'' *Journées d'automne*, Paris, November 1999, (in French), p. 174.
[4] Sutcliffe, M. P. F., 1988, ''Surface Asperity Deformation in Metal Forming Processes,'' Int. J. Mech. Sci., **30**, pp. 847–868.
[5] Sheu, S., and Wilson, W. R. D., 1983, ''Flattening of Workpiece Surface Asperities in Metalforming,'' *Proc. NAMRC XI*, pp. 172–178.
[6] Sutcliffe, M. P. F., 1999, ''Flattening of Random Rough Surfaces in Metal Forming,'' ASME J. Tribol., **12**, pp. 433–440.
[7] Wilson, W. R. D., and Walowit, J. A., 1972, ''An Isothermal Hydrodynamic Lubrication Theory for Strip With Front and Back Tension,'' *Tribology Convention, Institute of Mechanical Engineers*, London, pp. 164–172.
[8] Sutcliffe, M. P. F., and Johnson, K. L., 1990, ''Lubrication in Cold Strip Rolling in the 'Mixed' Regime,'' Proc. Instn Mech Engrs, **204**, pp. 249–261.
[9] Sheu, S., and Wilson, W. R. D., 1994, ''Mixed Lubrication of Strip Rolling,'' Tribol. Trans., **37**, pp. 483–493.
[10] Lo, S. W., 1994, ''A Study on the Flow Phenomena in the Mixed Lubrication Regime by Porous Medium Model,'' ASME J. Tribol., **116**, pp. 640–647.
[11] Kudo, H., 1965, ''A Note on the Role of Microscopically Trapped Lubricant at the Tool-Work Interface,'' Int. J. Mech. Sci., **7**, pp. 383–388.
[12] Mizuno, T., and Okamoto, M., 1982, ''Effects of Lubricant Viscosity at Pressure and Sliding Velocity on Lubricating Conditions in the Compression Friction Test on Sheet Metals,'' J. Lubr. Technol., **104**, pp. 53–59.
[13] Kudo, H., and Azushima, A., 1987, ''Interaction of Surface Microstructure and Lubricant in Metal Forming Tribology,'' *Proc. 2nd Int. Conf. on Adv. Tech. of Plasticity*, Stuttgart, pp. 373.
[14] Kihara, J., Kataoka, S., and Aizawat, T., 1992, ''Quantitative Evaluation of Micro-Pool Lubrication Mechanism,'' J. Jpn. Soc. Technol. Plasticity, **33–376**, pp. 556–561.
[15] Wang, Z., Dohda, K., Yokoi, N., and Haruyama, Y., 1997, ''Outflow Behavior of Lubricant in Micro Pits in Metal Forming,'' *First International Conference on Tribology in Manufacturing Processes*, Gifu, Japan, pp. 77–82.
[16] Lo, S., and Wilson, W. R. D., 1997, ''A Theoretical Model of Micro-Pool Lubrication in Metal Forming,'' *First International Conference on Tribology in Manufacturing Processes*, Gifu, Japan, pp. 83–90.
[17] Sheu, S., Hector, L. G., and Karabin, M. E., 1999, ''Two-Scale Surface Topography Design Scheme for Friction and Wear Control in Forging: Theory and Experiment,'' *The Integration of Material, Process and Product Design*, Zabaras, et al., eds., AA Balkema, Rotterdam, pp. 157–166.
[18] Lancaster, P. R., and Rowe, G. W., 1958, ''A Comparison of Boundary Lubricants Under Light and Heavy Loads,'' Wear, **2**, pp. 428–437.
[19] Thomson, P. F., and Hoggart, J. S., 1967, ''The Origin of Some Surface Defects on Rolled and Drawn Products,'' *20th Annual Conference*, Adelaide, pp. 189–198.
[20] Evans, C. R., and Johnson, K. L., 1986, ''The Rheological Properties of Elastohydrodynamic Lubricants,'' Proc. Instn Mech Engrs, **200C**, pp. 303–312.
[21] Sutcliffe, M. P. F., 1991, ''Measurements of the Rheological Properties of a Kerosene Metal-Rolling Lubricant,'' Proc. Instn Mech Engrs, **205B**, pp. 215–219.